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TREND OF AIRPLANE FLIGHT CHARACTERISTICS

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I. INTRODUCTION

The development of airplane flight characteristics (in contrast with the measurable performances) can be perceived directly by the pilot alone. The purpose of my lecture, however, is only to indicate the trend of this development, the object of which is to increase the safety of flight, and to explain in detail the most important problems. In connection with the results of flight tests it will be shown that a series of values which determine the characteristics of an airplane can be measured, thus making it possible to follow and to influence systematically the direction of development.

Airplane performances can be expressed numerically. Hence the state of development and the degree of progress attained can always be recognized. Likewise the direction of future development is clearly indicated. This direction is chiefly determined for commercial aviation by the problems of increasing the maximum speed, without greatly increasing the minimum speed, flight range, and economy of operation.

The development of the flight characteristics of controllability and stability can be perceived directly by the pilot alone, despite the possibility of measuring some of the values which determine them. It will be very difficult for anyone else to recognize improvements in the flight characteristics or establish any definite trend. There is such a trend, however, its goal being increased safety.

In what follows I shall describe the development of airplane characteristics since the war and indicate the

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direction I expect this development to take in the immediate future. I shall consider several problems which need to be solved. I am indebted to my colleague, W. Hübner, for several valuable suggestions.

II. DISCUSSION

1. The Behavior of an Airplane about Its Lateral Axis

I will first consider the behavior of an airplane with reference to its lateral axis, i.e., its longitudinal stability and controllability. At the end of the war, commercial aviation was in a state of development resulting from the endeavor to obtain greater maneuverability. The stability about the lateral axis was purposely kept small or even negative; the fuselage was generally short; the tail surfaces had small aspect ratios. The control surfaces had large balancing areas which, due to their form, were often inefficient. It was known that increased stability meant increased safety. It was sought, however, only on large airplanes which did not require any high degree of maneuverability. Present-day airplanes have relatively great stability in cruising with free elevator, i.e., with small lift coefficients. This stability was obtained chiefly by shifting the center of gravity forward. In recent airplanes the center of gravity lies between 15 and 35 percent of the mean wing chord, while more than 40 percent was common at the end of the war. The tail surfaces of present airplanes have large aspect ratios. Long fuselages are constantly increasing in favor. The movable tail surfaces have approximately the best relative dimensions. The control surfaces are so well balanced (for the most part internally) as to require very small control forces, even on the largest airplanes.

Figure 1 compares typical old and new airplane designs. The upper left-hand diagram represents a two-place observation biplane of 1917; the upper right-hand diagram, a two-seat 1932 sport airplane. The two lower diagrams afford a comparison of a 1921 airplane (left) and a 1931 commercial airplane. In order to facilitate comparison of fuselage length and wing span, the scales of the different drawings were so chosen as to make the spans of all four airplanes equal. The differences in the aspect ratios of the control surfaces and in the relative size of the movable parts are very noticeable. The elevator of the upper left-hand airplane has the triangular lateral balancing surfaces which were almost universal toward the end of the war. The older airplanes had wide ailerons of short span, while the recent airplanes have narrow ailerons with a span equal to about two thirds of the wing span, which is approximately the best value.

Great value is now attached to the requirement that, with free controls, the speed at which trim is obtained with normal engine power be not greatly different from that obtained with the engine throttled. With the stabilizer adjustment set for level flight at cruising speed, the trimming speed with the engine idling and the elevator free must not be more than 120 percent of the maximum horizontal speed. This requirement can be briefly illustrated by an example. Suppose the maximum horizontal speed of an airplane at full throttle is about 200 km (124 miles) per hour. The normal engine output will then yield a horizontal speed of about 180 km (112 miles) per hour. At this speed the airplane must be trimmed so that it will fly horizontally with the elevator free. If the engine is throttled, then, with the elevator free, the airplane will assume another condition of equilibrium, at which (the stabilizer adjustment and the location of the c.g. remaining the same) the speed will be greater than that for normal engine power. This speed must not exceed 120 percent of the maximum horizontal speed (which, in this example, was assumed to be 200 km/h), i.e., 240 km (149 miles) per hour. This requirement must be fulfilled for all permissible positions of the center of gravity of the airplane. It is also requisite that, even with the most advanced position of the c.g., tail landings shall be possible without changing the stabilizer adjustment.

Since the location of the c.g., especially in passenger airplanes, changes greatly with the load distribution, the required stability conditions must be fulfilled for a very great c.g. range. On commercial airplanes this range is about 9 percent of the mean wing chord. One of the latest commercial airplanes is airworthy for locations of the c.g. between 21 and 33 percent of the mean wing chord, i.e., for a range of 12 percent. The range is even greater, namely, 14 percent of the mean wing chord (from 15 to 29 percent) in one of the newest sport airplanes.

This variability of the c.g. with the loading must be lessened in future. The flight characteristics are affected in varying degree by the location of the c.g. Hence it is not possible to determine perfectly the characteristics of an airplane for so great a range of the c.g. location. The best characteristics of each airplane are fully attainable for only a single location of the c.g. Of course this does not mean that an airplane with only a small range of c.g. location will necessarily have better flight characteristics than one with a large range.

The problems, which still need to be solved with respect to the static stability and controllability about the lateral axis for improving the safety, are made obvious by plotting the characteristics of a recent airplane on the basis of flight tests. In figure 2, the lift coefficient is plotted against the elevator deflection for full throttle and for closed throttle. There is a striking difference in the course of the elevator-deflection curves for full throttle and closed throttle. At full throttle the attainment of maximum lift by commercial airplanes is never necessary. On the contrary, the danger of involuntary stalling must be avoided. The tests show, however, that very small elevator deflections suffice to effect great changes in the lift. The variation in the lift is great in the vicinity of the maximum lift. The attainment of the maximum lift is easily possible, as likewise the unintentional exceeding of the same. Slight variations in the elevator deflection may produce great accelerations and consequent great stresses in pulling up from level flight or pulling out of dives. On the contrary, with closed throttle, when, especially in landing, the easy attainment of the maximum lift is necessary, a great deflection of the elevator is required. With closed throttle the variation in the lift, with variation in the elevator deflection, diminishes with increasing lift. The cause of the difference in the course of the curves with full throttle and with closed throttle is to be sought in the varying degree of stability and dynamic pressure on the elevator. The degree of stability is represented in figure 3. It can be seen that, with increasing lift, the stability decreases with full throttle, while it increases with closed throttle.

Figure 4 shows the effectiveness of the elevator with full throttle and with closed throttle. In the latter case the effectiveness of the elevator is fairly constant. It is considerably greater at full throttle than at closed throttle and increases greatly with the lift. This increase in the elevator effectiveness is due to the fact that, with decreasing flight speed, there is an increase in the ratio of the dynamic pressure in the propeller slipstream to the dynamic pressure of flight. From the relations shown, it follows that improvements will be obtained by reducing the influence of the propeller slipstream on the stability and on the elevator effectiveness and by increasing the elevator effectiveness when flying with the engine throttled.

Especially on low-wing monoplanes, the maximum lift is smaller with closed throttle than with full throttle and, due to the blanketing effect of the idling propeller, is also smaller than without the propeller. Likewise the slope of the lift curve $dc_a/d\alpha$ is greater with full throttle than with closed throttle. Since the magnitude of the variation of lift due to change of direction of flow increases with the increase of slope of the lift curve, the stresses resulting from gusts would be greater in horizontal flight than in gliding flight with idling engine and the same speed. The problem of wing stresses from gusts has yet been but partially solved. Important conclusions were reached, however, from flight tests under the supervision of my colleague Dr. Taub, some of which were made in very stormy weather. Individual stresses from gusts were measured, which were as much as 2.2 times those occurring in unaccelerated flight. If the airplane had been flown at the maximum speed, the corresponding factor would be about 2.5.

The stability of German airplanes is greater with the elevators free than with them fixed. This is the result of the moment due to the weight of the controls, which are seldom balanced and then only on stunt-flying airplanes. It is to be expected that in future these moments will be balanced on all airplanes, as they are now in England. This would result in equalizing the stability with released and with fixed controls and in a reduction of the control forces. This reduction is considerable, especially in curvilinear flight, for the following reason. If the moments due to the weight of the controls are not balanced, i.e., if the c.g. of the elevator lies behind the axis, then these moments will increase in curvilinear flight, due to the centrifugal acceleration, and result in noseheaviness. The trimming condition with free control is thus shifted to smaller angles of attack, instead of to greater, as would be desirable for flying steady curves. This change takes place in the desired direction, however, when the c.g. of the elevator lies in front of the axis. In this location of the c.g., not only can curvilinear flights be made without any nose-heaviness, but even steady curves can be flown with free elevator.

The behavior of an airplane after disturbances is affected not only by the static stability, but also by the damping. The damping about the lateral axis is greater with fixed than with free elevator. Figure 5 shows the course of the dynamic pressure after a disturbance, once with free and once with fixed elevator. In both cases the magnitude of the disturbance, the moment of inertia, and the rearward location of the airplane c.g. were about the same. The vibrations die out much faster with fixed than with free elevator, showing that the damping is greater in the former case.

The great damping with fixed control might be utilized by the adoption of devices for the fixation of the elevator. In commercial flying the pilot's task consists principally in keeping the speed of the airplane constant. Test flights showed clearly how easy this can be when the elevator position is kept constant by locking the control. The use of locking devices can relieve the pilot more than anything else, even in blind flying. Locking devices were already in use during the war. They were applied, however, to the control stick and not to the elevator, as is desirable for the elimination of elasticity and the play in the control system.

The greater the damping about the lateral axis, the sooner an airplane with fixed control will come to rest after disturbances and gusts. It is often endeavored to increase the damping by the use of longer fuselages. The endeavor of the designer to increase the magnitude of the damping by lengthening the fuselage is opposed to the endeavor of the operator to utilize the fuselage largely for stowing loads. This increases the moment of inertia about the lateral axis and nullifies the improvement sought in lengthening the fuselage.

During flight the control surfaces undergo rapid and quite strong vibrations about their axes. Deflections up to about one degree were observed in flight tests. Vibration dampers are needed to save wear and fatigue of the controls.

The effective elevator range should allow complete utilization of the wing lift, but there must be stability about the lateral axis even with the maximum elevator deflection. There must be no instability about the lateral axis, as happens with present-day airplanes, especially at low speed, due to changes in the direction of the downwash from the separation of the flow in the middle of the wing. This requirement, which is, of course, valid for all loading conditions and positions of the throttle, now seems to be impossible of fulfillment, although, as regards safety, it is one of the most important tasks of the future.

The longitudinal stability of airplanes has been gradually improved and has already attained quite a high degree. The characteristics of airplanes have been improved with the stability, with no accompanying disadvantages. It is not known, however, whether the characteristics will be still further improved by further increases in the stability. Very great stability may possibly entail less favorable flight characteristics. It is conceivable that a very stable airplane would develop longitudinal oscillations and pitch violently in gusty weather. The question as to whether increasing the stability would entail such disadvantages, must be answered in order to decide whether further increase in stability is to be striven for as the direction for future development. For this purpose and on the recommendation of the D.V.L., the German Government has ordered an airplane with exceptionally great longitudinal stability, about five times as great as the present maximum. With this airplane, it is expected to determine what flight characteristics, what advantages and disadvantages are possessed by such stable airplanes. In this airplane, moreover, the distance from the elevator to the c.g. (that is, the damping about the lateral axis) is variable. Hence the effect of the damping, especially on the behavior in gusty weather, can be investigated.

Airplanes, for which great maneuverability is the prime requisite, will have less stability than hitherto. Great stability with fixed elevator reduces the angle-of-attack range attainable with the available up and down deflections of the elevator. Great stability with free elevator control may favor the occurrence of great accelerations in pulling up from level flight or pulling out of dives. If, for example, the control is released when the airplane is in the attitude of diving, it will level off automatically. The leveling off follows more quickly the greater the stability with free elevator control. During the leveling off, stresses of considerable magnitude may develop.

In this connection, attention is called to a common error. The view is often expressed that great elevator control forces are a sure protection against too sudden leveling off. It is therefore recommended to balance the elevator only a little or not at all. This view, however, is not necessarily correct. In very many instances the danger of leveling off too suddenly is increased by great control forces. This is always the case, when the state of equilibrium with free elevator lies at relatively large lift coefficients. If the elevator should be released in flight at high speed, i.e., with low lift coefficient, the airplane would automatically tend toward its state of equilibrium at a large angle of attack. At high speed the forces on the control stick are therefore in the direction of the control motion of leveling off. In order to level off slowly, the pilot must oppose these forces. Great control forces would therefore make it more difficult to level off slowly.

Although the stability of acrobatic airplanes should not be excessive, it should, however, cover the whole flight range, especially as regards spinning, and the change in the equilibrium with fixed control should be as small as possible.

2. The Behavior of Airplanes about Their Vertical and Longitudinal Axes

The development of the characteristics as regards the vertical and longitudinal axes of an airplane had not progressed very far at the end of the war. The works of Reissner and Gehlen on the combined stability about these axes, which are being studied at the present time, did not receive much consideration at that time.

Individual stability about the vertical and longitudinal axes was only accidentally present in a few cases. At the end of the war, most airplanes were apparently unstable or at best neutrally stable in yaw for the rudders were almost incomprehensibly small according to present conceptions. As an example, figure 6 shows side views of the same airplanes as shown in figure 1 and also on the same scale. The older airplanes are seen to have smaller vertical tail surfaces and shorter fuselages.

Visibility rather than aerodynamic considerations may have been given more weight during the war in determining the dihedral and sweepback of the wings. According to present conceptions the lateral control was inefficient and the control forces excessive. Attention has already been called to the principal reasons, the long chord and the short span of the ailerons.

As regards the efficiency of the ailerons and rudder and the reduction of the control forces, very great progress has been made. Great but not insuperable difficulties are still encountered in adjusting the effect of the individual controls. As regards the stability about the vertical and longitudinal axes, the development is yet very incomplete.

The specifications of the D.L.A. require stability about every axis in cruising flight, i.e., at small lift coefficients. They recommend for commercial airplanes simultaneous stability about both axes, i.e., lateral stability according to Reissner and Gehlen. This requirement had already been fulfilled by a commercial airplane, the BFW-M 20, before it was recommended in the specifications. Lateral stability assumes the existence and the harmonizing of the individual stabilities about the vertical and longitudinal axes.

As shown in the left-hand part of figure 7, the stability about the vertical axis, with conventional surfaces, decreases as the lift increases. At high lift coefficients, however, the stability about the vertical axis should be great. Otherwise unintentional yawing and skidding occur at large angles of attack. Due to these motions the flight speed diminishes very quickly and tilting motions occur (chiefly about the longitudinal axis), followed by a spin. It has therefore been sought (and quite successfully) to extend the stability about the vertical axis to large angles of attack by avoiding blanketing of the rudder as much as possible. The Focke-Wulf canard, whose characteristics correspond to the requirements of airworthiness, was made very stable about the vertical axis by the use of special devices up to angles of attack greater than those of maximum lift.

The disturbing effect of the propeller slipstream on the behavior of the airplane with respect to the vertical axis is likewise noticeable. With variation in the coefficient of propeller advance, the spiral motion of the slipstream changes and consequently the state of equilibrium about the vertical axis.

The right-hand part of figure 7 shows the rudder deflection required for straightaway flight. With closed throttle only small deflections (alternately left and right with increasing lift) are required for keeping the airplane on a straight course. At full throttle, on the contrary, the requisite rudder deflection constantly increases in the same direction. At maximum lift full rudder deflection is necessary on many airplanes for straightaway flight.

Considerable improvement can be effected by extending the rudder below, as well as above, the propeller axis. Such rudders, which would be installed symmetrically to the propeller axis, might considerably improve the controllability even in taxying, and especially on water.

Attempts will probably be made to counterbalance the variation of the state of equilibrium about the vertical axis by the use of vertical fins adjustable during flight. Existing difficulties can be overcome only in part by this means, which is to be recommended for counterbalancing the turning moment on a multi-engine airplane when one of the engines stops.

The effect of the slipstream seems to make for unsymmetrical stability about the vertical axis. Many airplanes behave differently, according to whether they are disturbed on the left or on the right. With such dissymmetry the advantages of the stability are not fully realizable. This condition can be remedied only by making the airplane symmetrical, at least with respect to the air flow. Such symmetry may perhaps be attained on a single-engine airplane by eliminating the spiral motion of the slipstream by means of guide vanes. British tests show that such guide vanes, despite their resistance, improve the flight performances. It might be well to emulate the British example and endeavor, as soon as possible, to obtain symmetry of air flow on a single-engine airplane.

The recommendation to lock the elevator for commercial flights applies also to the rudder. Attention is called to the fact that the foot control is too crude for the accurate maintenance of a given course and that an attempt will probably be made to develop a fine adjustment device for the rudder which can be operated by hand.

Stability about the longitudinal axis is obtained by the dihedral or sweepback of the wings. This stability decreases, however, with increasing lift. In present-day airplanes this stability is attained only for small lift coefficients. If it is to be extended to larger an-angles of attack, the dihedral must be much greater than hitherto.

It may be assumed that commercial airplanes of the future will have great longitudinal and lateral stability. It will be necessary to bring them into harmony with one another, since the longitudinal and lateral movements are interdependent. It has been found that laterally stable airplanes after disturbances, while returning to their original state of equilibrium in turning about their vertical and longitudinal axes, also rotate about their lateral axes. This causes considerable variation in the longitudinal attitude, speed, and flight altitude. Perhaps this coordination of the lateral and longitudinal motions is a result of the gyroscopic moments of the propeller; perhaps, by a corresponding coordination of the individual stabilities, it can be so adjusted that the longitudinal oscillations will be small.

The ultimate goal is an airplane whose operation does not require continuous manipulation of the controls for maintaining its equilibrium, but only in "directing," i.e., to keep on the desired course. Even this task of the pilot will be greatly lightened by the use of automatic course controls.

Laterally stable airplanes are characterized by a pronounced dihedral or sweepback of the wings and by great damping but moderate stability about the vertical axis. Both these conditions require large rudders and long fuselages, when the fuselage types have no inherent stability. The rudders and fuselages will be similar to those of the Messerschmidt and Rohrbach airplanes.

3. Behavior at Large Angles of Attack

The dangers of flight at large angles of attack are well known. Although they have been reduced in recent airplanes, they are still present to a considerable degree.

With increasing angle of attack, as already mentioned, the longitudinal stability decreases at full throttle and increases with closed throttle, while the stability about the longitudinal axis and about the vertical axis decreases. Moreover, with increasing lift, the damping about the longitudinal axis diminishes so rapidly that it reaches zero in the vicinity of the maximum lift.

According to how rapidly the various stability characteristics change, the following phenomena will occur in gradual stalling:

a) On pulling the elevator control, the airplane pitches suddenly forward;

b) The airplane yaws, skids, loses speed, and sideslips;

c) The airplane tips sidewise without previous yawing, due to the decrease in the damping about the longitudinal axis.

All three phenomena are alike dangerous, especially at a low altitude. It is desirable that neither of the described phenomena shall occur, i.e., that stability and equilibrium about all the axes shall exist at all attainable angles of attack. It will not be possible to attain this goal in the near future, since the total lift range of the wing must be utilized.

The immediate goal is the prevention of sudden turns and the obtention of control effects making it possible to counteract every unstable motion. Moreover, there will always be a universal endeavor to extend the damping about the longitudinal axis up to the maximum lift of the wing.

4. Landing Characteristics

With perfect flight characteristics, the difficulties of landing depend on the landing speed, the length of the landing run and the smallness of the path angle just before landing. Even at high wing loading, the landing speed is now kept within safe limits by the use of wings with high maximum lift. The landing runs are shortened by the use of wheel brakes. With the increase in the aerodynamic refinement of airplanes the flight path just before landing has constantly grown flatter. There are two ways to shorten the landing glide:

a) Landing in the stalled condition by making the angle of glide greater than in normal flight;

b) Using devices for varying the angle of glide without exceeding the maximum lift.

Landing in stalled flight assumes adequate controllability in this condition. This stage of development has not yet been even approximately attained. Even with adequate controllability, the difficulties of such a landing would be great, since the leveling off would have to be accomplished by reducing the angle of attack.

Quicker practical results can be expected from the second method, varying the angle of glide by special controls without leaving the range of normal flight. Such a control, with the aid of which the lift distribution and consequently the induced drag can be altered, was developed and tested by the D.V.L. according to Hübner's specifications. This device, although in a simple experimental form, enabled a variability of over 60 percent in the angle of glide and over 40 percent in the length of the landing glide. The control of such a device is very much simpler than landing in a stalled condition.

III. CONCLUSION

I think I have mentioned the most important problems in the improvement of flight characteristics. They are: the extension of stability about the airplane axes to the whole flight range; coordination of the individual stabilities for obtaining stability of coordinated motions; diminution of the disturbing effect of the slipstream; and increasing the range of the angle of glide.

The immediate goal of these problems is the development of flight characteristics in the direction of increasing the safety. The considerations apply, however, only to airplane types whose behavior is well known, i.e., to airplanes of the conventional type and to the canard type. For the development of the tailless and windmill (autogiro) airplane types, the knowledge of their properties and possibilities is still inadequate.

When I said that the characteristics of the conventional and canard types are known to us, I had in mind the progress made since the war. We are now able to determine the characteristics of an airplane qualitatively or quantitatively and thereby to promote development in the directions shown by practical experience to be the most expedient. My department is cooperating in this development by determining the characteristics of the airplanes and clarifying their relations to the aerodynamic stresses.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

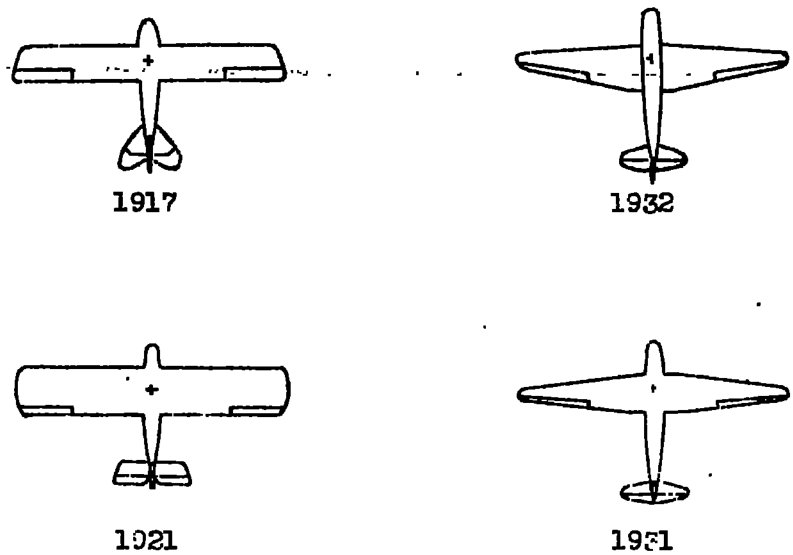

Figure 1.- Comparison of horizontal tail surfaces of old and new airplanes.

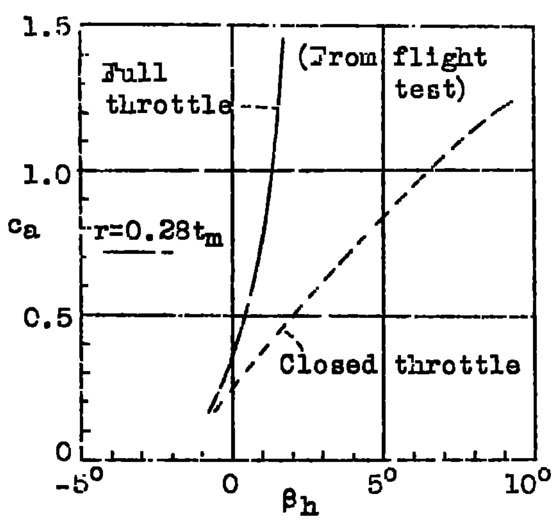

Figure 2.- Lift coefficient c_a plotted against elevator deflection β_h

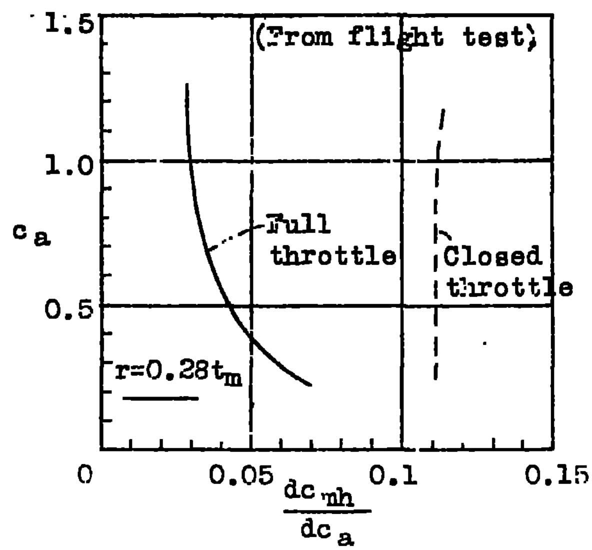

Figure 3.- Lift coefficient c_a plotted against static longitudinal stability. $\frac{dc_{mh}}{dc_a}$

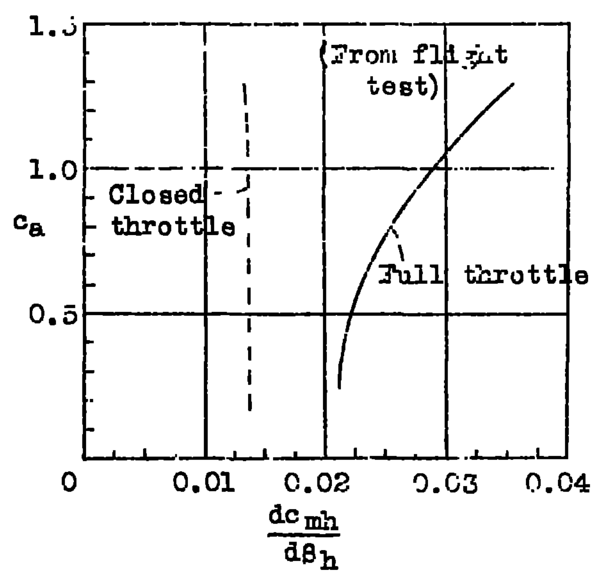

Figure 4.- Lift coefficient c_a plotted against static elevator effect $\frac{dc_{mh}}{d\beta_h}$

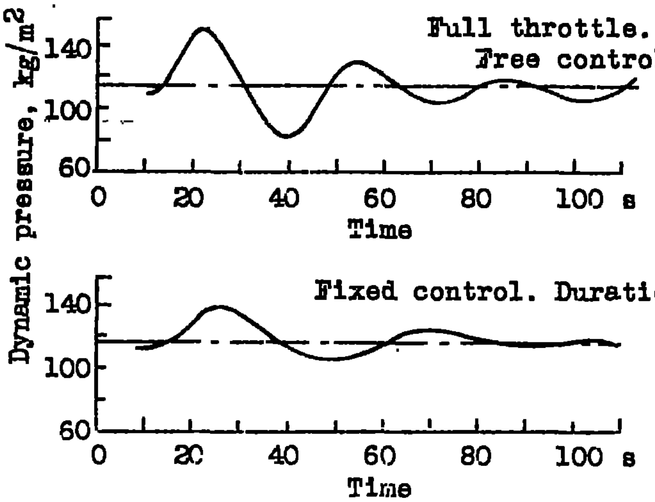

Figure 5.- Course of dynamic pressure with longitudinal vibrations for free elevator and for fixed elevator.

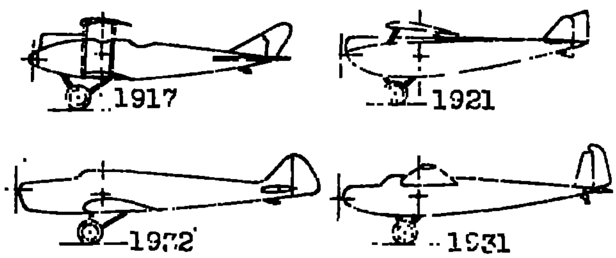

Figure 6.- Comparison of vertical tail surfaces of old and new airplanes.

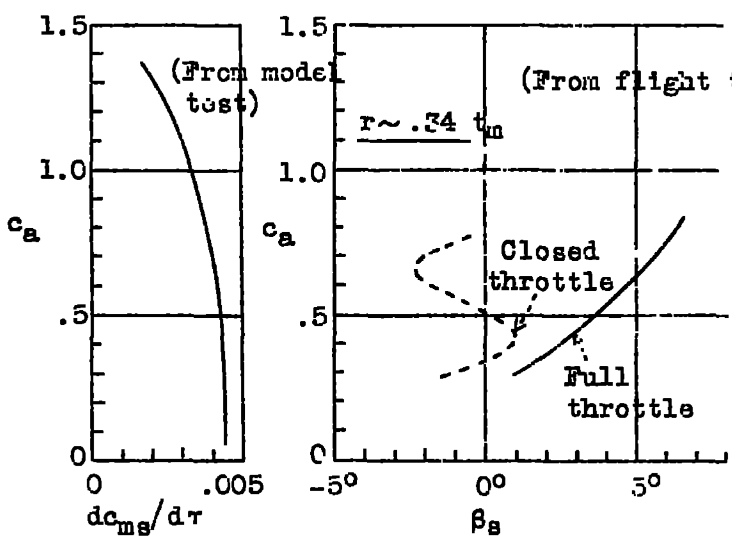

Figure 7.- Lift coefficient c_a plotted against static stability $dc_{ms}/d\tau$ about vertical axis and against rudder deflection β_s for straightaway flight.